

DLRs space qualifiable multi-fingered DEXHAND

Armin Wedler, Maxime Chalon, Andreas Baumann, Wieland Bertleff, Alexander Beyer, Robert Burger
Joerg Butterfass, Markus Grebenstein, Robin Gruber, Franz Hacker, Erich Kraemer, Klaus Landzettel,
Maximilian Maier, Hans-Juergen Sedlmayr, Nikolaus Seitz, Fabian Wappler,
Bertram Willberg, Thomas Wimboeck, Frederic Didot, Gerd Hirzinger

Institute of Robotics and Mechatronics, German Aerospace Center (DLR), Wessling, Germany

Contact: Armin.Wedler@dlr.de; +49(0)8153/28-1849

Abstract—Despite the progress since the first attempts of mankind to explore space, it appears that sending man in space remains challenging. While robotic systems are not yet ready to replace human presence, they provide an excellent support for astronauts during maintenance and hazardous tasks. This paper presents the development of a space qualified multi-fingered robotic hand and highlights the most interesting challenges. The design concept, the mechanical structure, the electronics architecture and the control system are presented throughout this global overview paper.

INTRODUCTION

The human intelligence is necessary to provide reactivity and adaptation that computer systems, especially the ones for space application, are lacking. However, the risks and associated costs of sending human beings in space are a strong limiting factor. While robotic systems are not yet ready to replace humans, they provide an excellent support for astronauts during maintenance and hazardous tasks. Under control of a tele-manipulation system the robotic systems could replace most of the Extra Vehicular Activities (EVA). Semi-autonomous control could also be used for simple routine tasks.

The European Space Agency (ESA) is currently investigating solutions in order to bring teleoperated systems to the International Space Station (ISS).

The equipment and the tools on board of the ISS are primarily designed for humans. Hence, they are meant to be used with hand and arm. Moreover, if used in a tele-manipulation scenario, the mapping from the operator to the robotic system must be as intuitive as possible. It minimizes the learning time, the user fatigue and improves execution speed. Upon those arguments, ESA decided to develop an EVA capable hand/arm system.

Similar projects are lead by JPL, with the hand of Robonaut [1], or at the University of Laval, with the SARAH hand [2].

This paper presents the development of an EVA qualifiable dexterous robotic hand (Fig. 1). This development is fulfilled within the framework of a direct contract between the German Aerospace Agency (DLR) Institute of Robotics and Mechatronics and the European Space Agency (ESA) Department of Robotics. The project will be presented based on the Final Design Review stage. It is an overview of the

technical decisions in the mechanical design, electronics and software systems.

The first part presents the main requirements for the system and explains how the general concepts have been selected. The second part "reveals" the mechanical structure, the tendon actuation system and the torque sensor implementation. The third part concentrates on the space specific electronic design features and on the critical issue of heat dissipation. The fourth part gives an overview of the control system, controller architecture and software distribution.

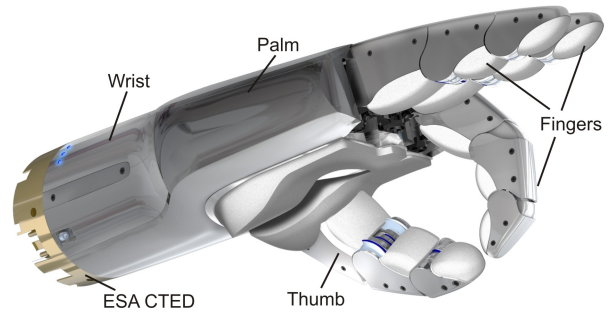


Fig. 1. Rendered CAD model of DEXHAND

I. SYSTEM OVERVIEW

The development of a torque controlled multi-fingered hand is a domain in which the DLR has a long standing history [3]–[6]. However, providing a space compliant product is a complex multi-domain problem. The DEXHAND is designed to be able to perform a set of generic tasks that are space oriented. For example, the removal of a multi layered insulation (MLI) cover or the manipulation of a handle. This section presents how the design concept and the architecture of the hand are selected based on the hand capability requirements.

A. Requirements

The design of the Dexhand are driven by its required capabilities. Some constraints are purely technical: operating temperature, maximum fingertip forces, joint velocity, but others are functional, such as grasping and operating a pistol grip tool (a space version of an electric driller). The desired capabilities must be translated into technical requirements

that result in a trade-off between system complexity, capabilities, reliability, volume, weight and cost. Fig. 2 reports an example of a top level functional requirement.

Requirement:	OPS-1
The DEXHAND shall be able to grasp the following EVA tools: <ul style="list-style-type: none"> • Pliers, and support their operations • Scissors, and support their operations • Small cutter and support its operations • Brush, and support its operations • Hammer, and support its operations • Scoop, and support its operations • Cutter, and support its operations • Tether(s), and support its operations • Allen wrench, and support its operations • Pistol grip tool (automatic screw driver) and support its trigger switch actuation 	
Comment: Successful operation of the tools implies force closure of the grasp. Note that preferably form closure should be achieved.	

Fig. 2. Requirements for the Dexhand (example)

B. Concepts

In the robotic community, hands are ranging from the simplest grippers to the most advanced biomimetic devices. The design space (i.e. the possible design solutions) of hands is extremely large, therefore, the first part of the project was to select a concept that would fit to the initial requirements. Examples of parameters that must be selected are:

- Number of fingers
- Number of degrees of freedom (DoF) per finger
- Number of actuated DoFs
- Placement of the fingers in the hand
- Shape of the fingertips
- Size of the fingers
- Etc ...

Certainly, each finger DoF brings more capabilities but increases the number of parts. The use of multiple small actuators, instead of a single large actuator, increases the capabilities to distribute power losses, might provide redundancy, and usually provides a better form factor. However, the raw power density is reduced. The control complexity and the number of sensors must also be increased in order to take advantage of the available degrees of freedom.

The principle parameters are selected based on the manipulation experience gathered with the DLR Hand II and DLR/HIT hand. A parameter refinement is done by simulating grasps with each object of the EVA tool list.

For example, in order to perform trigger actuation of the pistol grip tool, while maintaining tool stability, it appears that at least three fingers are required.

For fine manipulation, the shape of the fingertips is playing a key role. In Fig. 3, several shapes are compared with respect to rolling, maximum load and the ability to pick up small objects. The DEXHAND is using a variable curvature with a flat end fingertip shape.

C. Architecture

The DEXHAND system is developed for use with a robotic arm (Dexarm) designed and realized by Selex


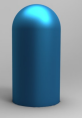
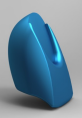
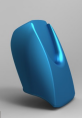
	Square	Hemi-spherical	Variable curvature	Variable curvature flat end
Finger tip shape				
Small object picking	+++	-	++	++
Rolling	--	+++	++	++
Maximum load on the finger tip during pinch grasp	++	-	+	+++

Fig. 3. Example of fingertip shapes

Galileo. The complete DEXHAND CAD rendering with its subcomponents is shown in Fig. 1.

The hand has 12 actuated degrees of freedom (DOFs), distributed in 4 fingers with 3 degrees of freedom each. Fig. 1 presents the latest state of the CAD model and Fig. 7 shows a photo of the DEXHAND prototype. The actuation system is based on geared motors followed by a tendon transmission system (cf. section II). The motors are controlled using a combination of a DSP, FPGA and motor controllers. Joint torque measurements are available and realized with full bridge strain gauge sensors. Multiple temperature sensors are available to protect the system against overheating and freezing. The control system of the hand is able to run entirely inside the hand. The DEXHAND is required to communicate over a CAN bus with a common VxWorks communication controller. The communication to control the Dexarm is routed as well through a real-time VxWorks system. It will allow the hand and the arm controllers to be tightly synchronized in the future.

II. MECHANICAL STRUCTURE

In the DEXHAND, modular fingers are used in order to increase the system reliability. It also improves the cost efficiency of the project. However, based on a kinematic analysis and the experience from the DLR Hand II, a special finger is used for the thumb. As shown in [7], the thumb deserves a special treatment in order to increase the hand dexterity. For example, in order to properly oppose to the other fingers the thumb should have at least twice the maximum fingertip force. The DEXHAND fingers are design to actively produce a fingertip force of 25 N (for the stretched finger) while withstanding 100 N passively.

The transmission system is using polymer dyneema tendons and harmonic drives in order to bring the motor torque to the joints. The concept keeps the extremities (the fingers) with less and radiation uncritical electronics as possible to improve shielding. The shielding strategy consists in housing the whole electronic system in an aluminium shell at least 2 mm thick.

This leads to a fully EMI sealed hand body containing: the drives, the power electronics and the communication

electronics. The only exceptions are the torque sensors, based on strain gauges, and some temperature sensors, which have to be placed in the fingers. The design successfully englobes all electronic systems in its protective housing.

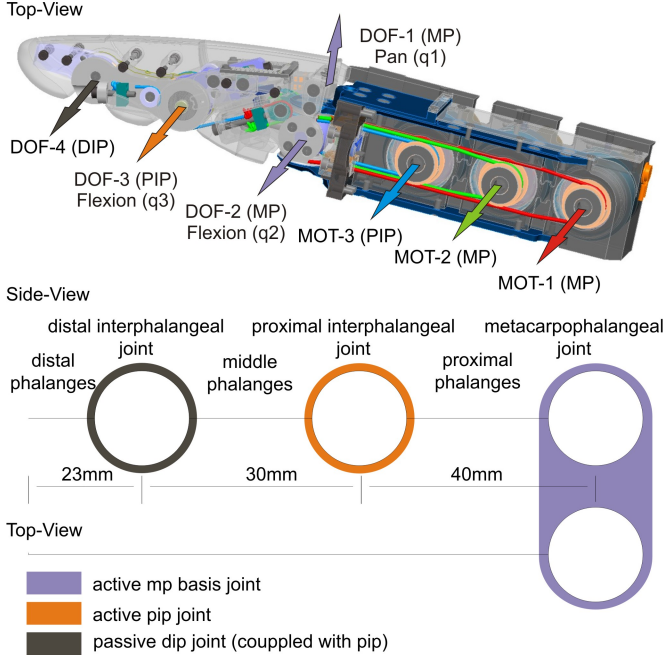


Fig. 4. Actuation principle of the fingers

The cardanic metacarpophalangeal (MP) base joint is driven by two motors. Due to the coupling of the tendons in the MP joint the two motor torques can be used together for one degree of freedom (DOF) of the base joint. This aspect opens the possibility of using the same motors for the base joint and the proximal interphalangeal (PIP) joint. Indeed, due to the difference of lever length (pulley radius) the required torques are scaled dependent to each joint. The PIP joint has a fixed coupling with the distal interphalangeal joint (DIP) with a ratio of 1:1. In Fig. 4 the section lengths, joint positions and definitions are shown.

The coupling matrix P , which relates motor velocity θ with joint velocity q is:

$$\dot{\theta} = P\dot{q} \quad (1)$$

$$P = \frac{1}{r_p} \begin{bmatrix} r_1 & r_2 & 0 \\ -r_1 & r_2 & 0 \\ r_{13} & r_{23} & r_3 \end{bmatrix} \quad (2)$$

Where r_p is the motor pulley radius, r_1, r_2 and r_3 , are the joint pulley radius, and r_{13} and r_{23} are the pulley radius of the PIP tendons in the base. Given that the coupling matrix is not configuration dependant, the relationship can be integrated in:

$$\theta = Pq \quad (3)$$

The motor unit for Dexhand has been developed based on the DLR / Robodrive [8] ILM 25 motor including the gearing of a harmonic drive [9] HFUC 8 with a transmission ratio of

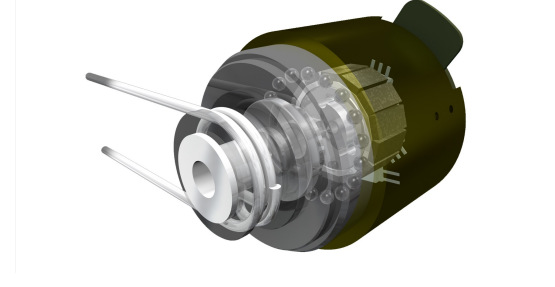


Fig. 5. Drive unit with ILM 25 and harmonic drive gearing

100:1. The whole unit fits into a cylinder of 27 mm diameter and a length of 17.5 mm with a weight of 46 g (Fig. 5).

The unit provides a continuous torque of 2.4 Nm with peaks up to 9 Nm which is the maximum peak torque of the gearing. In the DEXHAND, the motor has been electronically limited to 2 Nm for power reasons. Each actuated joint has a reference mark in the middle of its motion range. These reference marks are composed of a small magnet and a Hall-effect sensor located in the actuated joint. The joint torque measurement is implemented using a sensing body and a full bridge strain gauges sensors (Fig. 6). The torque sensors are all physically located in the proximal finger link. Therefore the sensor for the PIP/DIP-joints measures the reaction torque of the coupling tendons.

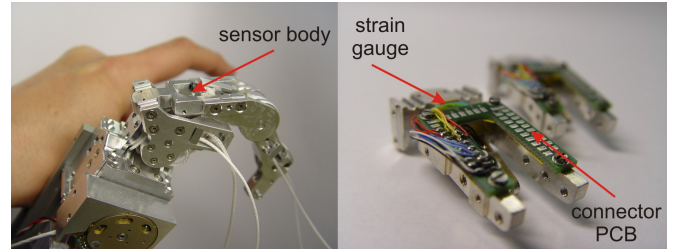


Fig. 6. left: Finger without housing, right: Strain gauge sensor body

All sensors, except one of the reference sensors of the MP joint, are located and mounted in one mechanical part. This part also contains the pull relief of the wires, as well as the shield connection of the cable from the fingers to the electronics in the palm. This simplifies the assembly and the maintenance of the finger. Special care was taken in the design of the sensor body in order to prevent temperature drift. The force measurements obtained in a thermal chamber from -50° to 70° confirmed the measurement stability. The palm structure consists of 11 main segments. These segments are massive aluminium parts to improve heat transfer and increase the thermal inertia. The modules of the DEXHAND are four different ensembles representing the ring-, middle-, index- and thumb finger actuation units. A unit includes the tendon guidance from the motor pulleys to the MP and DIP joint. The palm surface mainly consists of the outer shell parts. Furthermore, all parts are designed without sharp edges. They are optimized for ideal thermal allocation and minimum resistivity (Fig. 7 shows the hand without the palm

grasp pads).

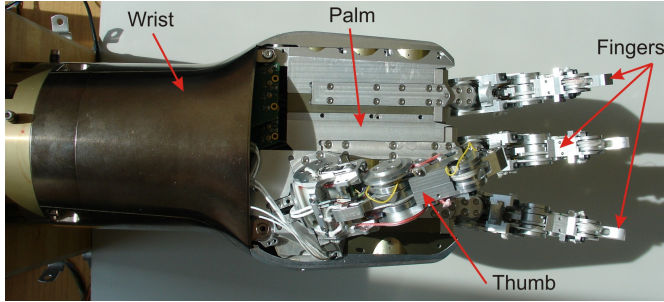


Fig. 7. Section view of Dexhand

The wrist houses all electronic parts. This includes the analog, the digital and the power circuit boards. The electronic boards are coupled to the palm assembly with connectors. The housing of the DEXHAND is composed of 2 mm aluminium shells. It is fully closed to provide EMC protection. During tests with 4 kV impulse at the fingertip and palm structure no failure has been detected. The final DEXHAND design is presented in Fig. 7. Furthermore the compact and also fully integrated housing of the electronic inside the wrist is shown in Fig. 8

III. ELECTRONICS

The design of outer space capable electronics faces 4 main challenges:

- radiation tolerance
- heat dissipation
- size/performance
- power limitation

Parts that are readily available for radiation duty are, in general, larger and have less performance than their industrial equivalents. As a general rule, one can expect to use only mature technologies, meaning 10, if not 20, years old. However, based on the successful results of the ROKVISS experiment [10], in which mostly standard automotive parts have been used in outer space for more than 5 years. It has been decided to use the same strategy and to perform system level tests to control the results. Moreover, designing a human sized hand with 12 active joints requires both high-performance and small electronic components. This is not feasible with only radiation tolerant parts. Therefore, the existing off-the-shelf solutions have been evaluated focusing on the possible usability for outer space applications. The chosen motor controller components have been successfully tested in a rad-test-facility under a 120 Gy irradiation. The DEXHAND prototypes will not be equipped with radiation tolerant components. However, all electronic part, for example such as the DSP, FPGA, D-RAM et cetera, used in the DEXHAND are, in size and function, equivalent to the radiation tolerant counterparts. The resulting board placement is shown in Fig. 8.

All the PCBs are functionally divided directly behind the mechanical hand connector. The input filter board absorbs noise coming from the hand carrier (e.g. the Dexarm) and

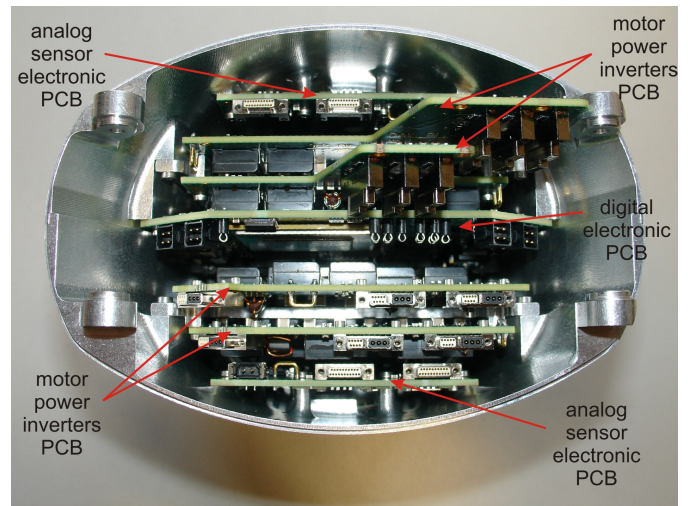


Fig. 8. PCB placement in the hand base (view from palm to wrist)

ensures that the hand device does not inject any spikes in the carrier. The power supply board, which additionally behave as a backplane to connect all horizontal PCBs of the stack, provides: global power limitation, soft-start, hot plugging circuitry and signal conditioning. Four horizontal PCBs connect each one finger with three motors. Two other horizontal PCBs are used for analog signal conversion of the strain gauge sensors. Fig. 8 shows the main digital electronic PCB which carries the DSP, the FPGA, the flash memory and the different RAMs.



Fig. 9. Main digital PCB containing DSP, FPGA, flash memory, D-RAM and M-RAM

The cables and connectors to connect the fingers and the motor units to the PCBs have been specially designed for this project. Those connectors are completely shielded and combine power lines and signal cables (see Fig.10). The connector includes a screwed mechanical fixation to ensure proper connection after the vibrations of the launch process.

The power distribution in the DEXHAND is reported in table I (see also Fig. 11).



Fig. 10. Special connectors including power and signal cables

TABLE I
POWER DISTRIBUTION IN WATTS

Case	Full Power	Standby	Nominal
Input filter	5	2	3.5
Backplane PCB	6	6	6
Sensor PCB	2	2	2
Power inverters	24	3.6	14
Controller PCB	5	5	5
Motors	58	0	28
Total	100	18.6	58.5

Because of the absence of convective heat exchange, heat transfers are only the result of conduction¹ and radiation. Therefore, terrestrial design patterns can not be used directly (no heat sink, no fan). The losses due to the motors are not an important issue since they can be modulated by the software, slowing down and limiting the torque for example. Those losses are limiting the maximum operation time, imposing cooling periods once the maximal operational temperature is reached. The communication electronics and the digital circuits are more important because they can not easily be switched off. They define the relaxation behavior of the DEXHAND. Thermal simulation results, in the case of a nominal operation during 1749 secondes, are depicted in Fig. 11. The DEXHAND is assumed to be isolated at the wrist interface and to receive radiated power only from the sun and the ISS.

IV. SOFTWARE AND CONTROL

As presented in the previous section, the hand carries a DSP and a FPGA. The FPGA is used for low level, high speed, functional blocks as depicted in Fig. 12. In the DSP, functional blocks such as calibration tables, impedance control loops, communication and safety systems are implemented (Fig. 13). The controller itself is an impedance controller running at 1 kHz.

A. Software

The communication to the system (Fig. 14) is done via CAN bus, on which no hard real time data is allowed. The commands to the system are always asynchronous. However, in the case of a telemanipulation scenario, the

¹Even though attached to the wrist of the DexArm only a limited amount of heat may be transferred.

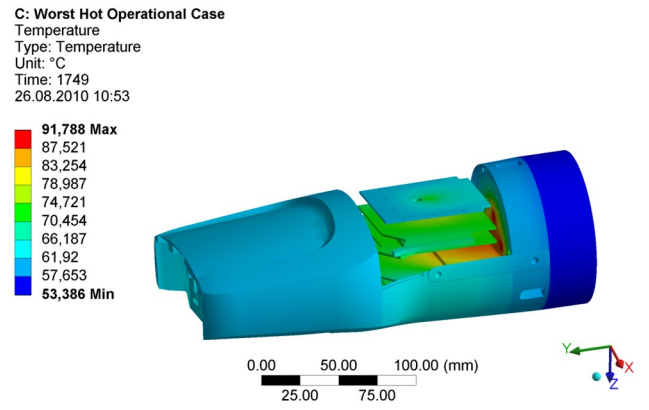


Fig. 11. Thermal behaviour after 1749 secondes of nominal operation (cf. table I). The hottest point is located on the DSP (in the digital electronic board)

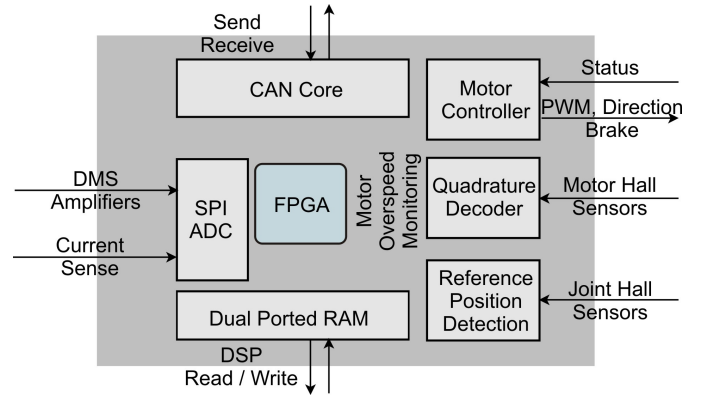


Fig. 12. Functions implemented in the FPGA

real-time system VxWorks machine is used to establish the data exchange between the data glove data source and the DEXHAND. The VxWorks system is used to monitor the communication bus and provide a TCP/IP communication interface from any standard operating system.

B. Control

In order to set the joint position of the fingers, while controlling the applied joint torques, a joint impedance controller is used. Table II reports the variable definitions.

The simplified dynamics model of the finger is:

$$M(q)\ddot{q} + B(\dot{q}, q) + G(q) = \tau_{friction} + \tau_m + \tau_{ext} \quad (4)$$

Where all quantities are expressed in the joint coordinates and are transformed in joint coordinates using the coupling matrix P (see sec. II):

$$\dot{\theta} = P\dot{q} \quad (5)$$

Using the principle of virtual works:

$$\tau_q = P^T \tau_{theta} \quad (6)$$

$$\tau_{theta} = P^{-T} \tau_m \quad (7)$$

The stiffness control law can be written:

$$\tau_{imp} = K_{imp}(q - q_{des}) \quad (8)$$

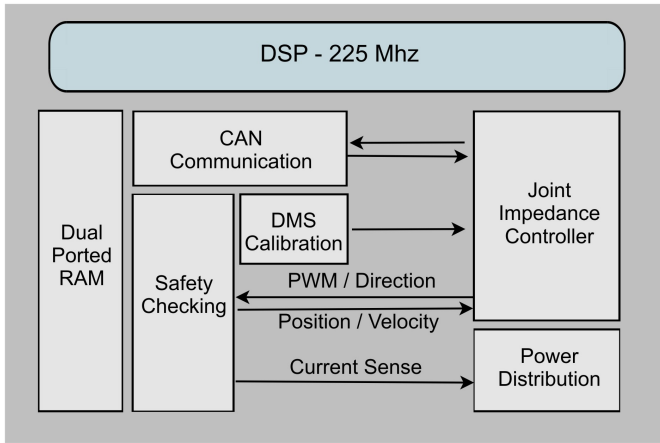


Fig. 13. Functions implemented in the DSP

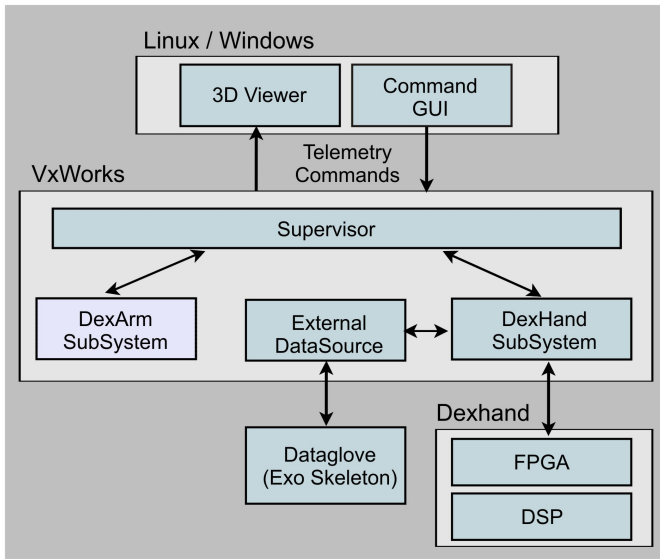


Fig. 14. Communication Architecture

$$\tau_{ref} = \tau_{imp} + \tau_{grav} + \tau_{friction} \quad (9)$$

$$\tau_m = K(\tau_{ref} - \hat{\tau}) + \tau_{ref} \quad (10)$$

Replaced in eq. (4) it yields the desired static behaviour:

$$\tau_{ext} = K_{imp}(q - q_{des}) \quad (11)$$

CONCLUSION

This paper presented an overview of the DEXHAND project. The development is based on the experience of DLR in designing and building multi-fingered robot hands. The experience acquired with the ROKVISS project also guided many decisions.

It should be noted that the biggest issue in term of thermal control are the digital electronic circuits and not the motors or the power inverters. Indeed, they have very little dissipation capabilities.

The radiation and EMC issues are mainly solved by using a thick enclosing aluminum shell. The fingers proved to be

TABLE II
VARIABLE DEFINITION

Symbol	Unit	Description
q	rad	measured joint position
q_{des}	rad	desired joint position
θ	rad	measured motor position
θ_{des}	rad	desired motor position
τ_q	Nm	commanded joint torque
$\hat{\tau}_q$	Nm	estimated joint torque
τ_θ	Nm	motor torque
K_{imp}	Nm/rad	prescribed joint stiffness
τ_{grav}	Nm/rad	joint torque due to gravity
$\tau_{friction}$	Nm/rad	joint torque due to friction
M	kg	mass matrix in joint coordinates
B		centrifugal and coriolis terms
G		gravity terms
P		coupling matrix

capable of applying 25N at the fingertip, and can withstand 100N impact load.

The control system runs entirely in the DEXHAND, allowing very low communication bandwidth requirements. The structure permits a future tight connection between the Dexarm and the DEXHAND, to perform hand/arm operations.

ACKNOWLEDGMENT

The authors would like to thank the DEXHAND team at DLR, as well as, the ESA for the opportunity to develop a EVA capable hand. The DEXHAND Project has been founded with the ESA Contract No. 21929/08/NL/EM.

REFERENCES

- [1] M. A. Diftler, R. O. Ambrose, S. M. Goza, K. Tyree, and E. Huber, "Robonaut Mobile Autonomy: Initial Experiments," in *IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April 2005, pp. 1437 – 1442.
- [2] B. Rubinger, M. Brousseau, J. Lymer, C. M. Gosselin, T. Laliberté, and J.-C. Piedboeuf, "A novel robotic hand - sarah for operations on the international space station," *Proceeding of the ASTRA 2002 Workshop*, 2002.
- [3] J. Butterfaß, G. Hirzinger, S. Knoch, and H. Liu, "DLR's multisensory hand part i: Hard- and software architecture," *Proceedings of the IEEE Int. Conf. on Robotics and Automation*, 1998.
- [4] C. Borst, M. Fischer, S. Haidacher, H. Liu, and G. Hirzinger, "DLR hand II: experiments and experiences with an anthropomorphic hand," in *ICRA*, 2003, pp. 702–707.
- [5] Z. Chen, N. Y. Lii, T. Wimboeck, S. Fan, M. Jin, C. H. Borst, and H. Liu, "Experimental study on impedance control for the five-fingered dexterous robot hand dlr-hit ii," *Proceedings - IEEE IROS*, 2010.
- [6] M. Grebenstein and P. van der Smagt, "Antagonism for a highly anthropomorphic hand arm system," *Advanced Robotics*, no. 22, pp. 39–55, 2008.
- [7] M. Chalon, T. Wimböck, M. Grebenstein, and G. Hirzinger, "The thumb: Guidelines for a robotic design," in *IROS*, 2010.
- [8] RoboDrive. (2009) Website of the robodrive gmbh company. [Online]. Available: <http://www.robodrive.de/>
- [9] Harmonic-Drive. (2009) just move it! Website of the Harmonic Drive AG Company. [Online]. Available: <http://www.harmonicdrive.de/>
- [10] G. Hirzinger, K. Landzettel, D. Reintsema, C. Preusche, A. Albu-Schäfer, B. Rebele, and M. Turk, "Rokviss - robotics component verification on iss," 2005.